Robotic Space Colonies

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Abstract

Robotic colonies, consisting of teams of robots operating cooperatively at a remote location in outer space, are among the most challenging visions in space exploration. There are many types of missions enabled by such a vision: permanent observatories and other science collecting stations on planetary surfaces; roaming caravans of mobile robots exploring large territorial areas; and establishing power, communications, and other infrastructures to pave the way for permanent human presence beyond Earth orbit. Many major challenges have been identified to date. These challenges include that of how to achieve long-life and even permanent presence. Another challenge is that of creating robot teams with collective autonomy capable of responding to high-level group commands. Yet another challenge consists of synthesizing robot work crews to do heavy-duty cooperative work on planetary surfaces for drilling, terrain conditioning, carrying heavy objects, and assembling structural components and systems. This paper reviews recent advances in these technologies, with a particular focus on experimental state-of-the-art robot work crew system demonstrations at JPL, that are being conducted now to begin to realize the futuristic robotic colony vision.

1. Introduction

Space robotic colonies are perhaps one of the most advanced and exciting areas of today's space robotic research and technology development. A robotic colony can provide a permanent, continuous operational presence elsewhere in our solar system. Set up and operated by robots, possibly visited by humans – eventually perhaps populated by both – a colony is established, expanded and re-supplied using resources from Earth, and native, *in situ* resources. Begun as a small settlement (sometimes termed an outpost) and growing over multiple missions, robots – on Mars, for instance – could:

- Explore larger areas faster than current missions
- Set up a drilling system
- Dig continuously—seeking minerals and water
- Launch aerobots that fly on planetary atmospheres
- Establish and maintain nets of science and meteorological sensors, and
- Analyze surface and subsurface samples.

Pursuing the long-term goal to establish advanced robot and human-precursor bases throughout our solar system, NASA is developing fundamental robot-colony technologies to greatly enhance this exploration in the decades ahead. There are many possibilities for robotic colonies:

- Poles of Mars – to look carefully for water, evidence of life and climate changes
- Olympus Mons on Mars – to continuously study the solar system's largest volcano and monitor it for recent volcanic activity
- Mars Great Valley (Valles Marineris) – to search for water and understand the tectonic origins
- Lunar Observatories: to set up observatories that give warning of asteroids that might endanger Earth
- Asteroid Belt – to study and possibly mine raw materials
- Near-Earth Asteroids – to study and set up residence, understand how they are constructed and might be mined, or diverted if they become a threat.

Even further into deep space, possibilities for robotic colonies exist in orbit around the sun, to get an unobstructed view of the entire universe. Another possibility is that of stations on Europa, to penetrate its postulated frozen ocean and carry out a campaign to look for life beneath the ice. Titan, Saturn's largest moon, is the only one in our solar system with a thick atmosphere, rich in organic chemicals. A robotic colony that can stay there for a long time is a very attractive futuristic vision.

2. What Robotic Colonies Will Do and How

Robots in a colony could perform advanced science gathering, create continuous, long-term data sets of important environmental phenomena—not simply exploring a few meters from a landing site, or returning a handful of rock and soil samples. A miniature laboratory might analyze a wide variety of samples, sending only the most interesting to Earth. Sophisticated *in situ* analysis might seek present or past life on moons and planets and conduct in-depth studies of geological, atmospheric and climate evolution. Living things signal their presence by changing their essential elements' mix—carbon, hydrogen, nitrogen and oxygen—leaving their signature in surface materials, or living life forms. Robots examining the layers—epochs—of Mars' millions-of-years-old terrain, and inventorying water, carbon dioxide and isotopic carbon and oxygen, may find clues to life's origin and evolution.

2.1 Other roles for robotic colonies

Science-gathering colonies may be placed on Mars, Earth's moon, or an asteroid; in orbit around these bodies, or at their libration points. Permanent robotic colonies located in orbit or at libration points around Earth—and eventually Mars—could serve as sites to:

- Assemble, service, store, and launch future solar-system-exploration probes,
- Put huge telescopes capable of gathering images of planets in other solar systems, or
- Serve as a base for zero-gravity manufacturing facilities.

2.2 What would a colony look like?

Although different colonies are being considered for other solar-system bodies, we focus on Mars because of its great scientific potential and closeness to Earth.

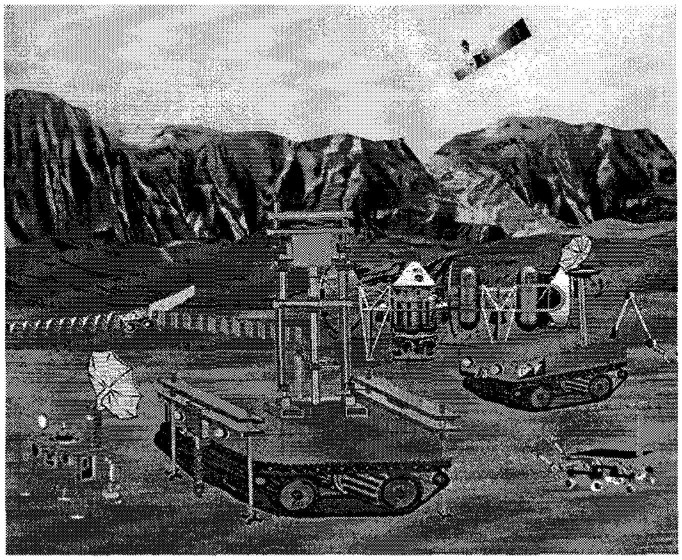

Fig. 1 Example of an advanced robot colony

Fig. 1 is an example of how a permanent robotic colony on Mars might look. Initially, solar power could provide energy to process samples, produce fuel and oxidants from *in situ* materials, and setup a drilling system to examine the subsurface. Using new power sources to launch aerobots and long-range rovers, robot colonies would continuously explore distant areas, and find and analyze the most interesting sites for subsequent robotic or human science follow up. Mars' robot colonies may be the critical link between robotic and human missions. To prepare for people, robotic crews would deploy essential surface equipment, and assemble habitats and energy generators. Humans would then explore firsthand, side by side with their mechanical helpers that would perform the more burdensome tasks.

3. Technology Challenges

The technical challenges to make the foregoing futuristic vision materialize are formidable.

3.1 Autonomous repair and replacement

To autonomously repair and reproduce themselves to keep the colony alive into the future, robots must be able to repair and upgrade their own hardware and software, and eventually perhaps develop advanced generations of themselves, with minimal help or re-supply from Earth. Increasingly complex steps, taken to approach this formidable task might include sequential development of technology to:

- Repair a failed robot by diagnosing its condition, take corrective action, i.e., swapping out solar panels, motors, etc.

- Allow two robots to make a third with *in situ* raw materials and pre-fabricated modular parts.

- Cannibalize robot parts to build a new one, and re-assign it the previous robot's responsibilities.

- React to an unplanned opportunity or challenge by enabling two or more robots to create distinctive robots—assemblers, load movers, thinkers, etc.

3.2 High Level Collective Robot Autonomy

Many different types of robots must combine their skills to accomplish the complex tasks expected of a colony, i.e., mapping a planet or moon surface's minerals, temperatures, barometric pressure and geological profile. But communications, command and control approaches and algorithms do not yet exist that let robots focus quickly and act decisively when danger threatens the robots or the colony. To operate a colony for long periods with slight human direction, robots must collectively and autonomously perform high-level commands like:

- **Prepare for summer expedition** – this high-level command means robots must manage energy, plan itineraries, find good samples, store resources, keep adequate records, etc.
- **Execute summer expedition** – teams of robots must collectively and autonomously execute plans, continuously monitor results, and actively manage a risky but venturesome trip.
- **Prepare for winter** – robots must ensure outpost safety and integrity; stock energy and other provisions, curtail activities to reduce risk, etc.

A more modest, but still very ambitious level of autonomy might involve operations more short-lived and closer to home. But, whether tasks are high-level and strategic, or merely daily and routine, robotic commands must be broken down into simpler commands such as:

- **Let's go** - like a squad leader, a robot lead calls the robot team, initiating a complex operation.
- **Bear left or right** –the robot-work crew moves a heavy object toward the left or the right.

- **Descend the steep cliff or crater** – plan paths downward, monitor progress while ensuring safety, verify intermediate goals during descent.
- **Select samples** – using predefined criteria, collect best samples for later analysis back at the base.
- **Job complete** – a task was successfully completed.

3.3 Self-Preservation

The collective-autonomy challenge is teaching robots to protect themselves from threats like major dust storms, live off the land, and utilize local resources—not re-supplies from Earth. A self-sustaining colony must balance using and generating energy—for example a rover fueled by methane and oxygen derived solely from Mars' carbon-dioxide-rich atmosphere and subsurface water. This *in situ* fuel does not pay for itself unless the energy that produced the methane and oxygen is less than the energy that drives the rovers' engines.

4. Robot Work Crew Experiments

We report the preliminary development and experimentation with such robotic work crew concepts, building on prior JPL work in autonomous planetary rovers and robots. Our new research focuses on definition of cooperating robots that can coordinate closely and continuously perform a site construction task such as the autonomous deployment of a solar photo-voltaic (PV) tent array. Such a Mars power station is an essential precursor to long duration robotic or human presence.

There are numerous challenges in this prototypical task. Problems include the cooperative manipulative acquisition of extended objects from a container storage depot, next the cooperative transport of such a container to the power array construction site, and then the physical deployment of the container into the array. Two features of this scenario are particularly salient in our ongoing work, which emphasizes the *"transport phase"* of the deployment operation. First is that of cooperative sensor-based autonomous traverse of two kinematically linked rovers across natural, uncertain terrain. Second is that of distributed force-motion control of this non-holonomic extended platform (each rover having a gimbal-mounted gripper that is instrumented for force-position in all axes, and compliance in one).

JPL has developed a tiered behavior control architecture for closely coupled operation of multiple robots, wherein mobility and control functions are derived as group compositions and coordination of more basic behaviors under the downward task decomposition of a multi-agent planner. The architecture is extensible and scales freely with regard to behavioral mechanisms and protocols it can host and fuse; re-mappable inter-robot communications (for both implicit and explicit networking) it can support; and the overall ability to functionally integrate heterogeneous, multi-purpose platforms. A Control Architecture for Multi-robot Planetary Outposts (*CAMPOUT*), some supporting simulations, and physical experimentation to date with two rovers carrying a model payload over natural terrain is reported(SCHENKER REFERENCE).

4.1 Issues in Robot Work Crew Research

We are investigating previously unexplored and important problems in multi-robot coordination to do cooperative work in the moving and handling of objects on sloped and rocky planetary terrain. This research is of relevance to a wide variety of surface missions that require moving of either human made or natural objects on planetary surfaces. These mission operations include deployment of solar panels and other large infrastructures; movement of rocks, containers and other small objects; deployment of multiple sensor arrays for measurement and observation; anchoring of deployed structures; and clearing of terrain. The robot work crews could operate in a purely robotic mode, or they could assist astronauts conducting extensive extra-vehicular operations.

This research is of interest because coordinated movement and mechanical force application has received little attention in robot team research, although a body of research is beginning to emerge. In addition, complexities due to terrain slopes and roughness add a variability that goes beyond currently solved problems in a field that is in its relative infancy. Prior and current research has focused mostly on group movement, along with its associated issues of communication, control, and navigation. Research has focused on three main types of activities: foraging, formation marching, and object (e.g. box) pushing. Foraging is the collective search and retrieval of a set of objects distributed over an area. The research focuses on how to get a group of robots to behave efficiently. Though retrieval is often part of the task, little effort has been made to describe the local actions to do the actual transport. Formation marching requires a group of robots to move from one point to another, while maintaining a constant geometric pattern and avoiding obstacles. Finally, box pushing requires at least two robots to work together to push an object from one point to another. As valuable as this early research is, it addresses mostly task planning and communication requirements for robot teams that are not physically linked. Much research remains to be done in mechanically connected multi-robot systems that are collectively conducting a complex "work" operation.

4.2 Current Experimental Results

Robots are learning to work together, for example, to share modular sensors and controls. But researchers are engaged in overcoming the challenges that might be found when planetary robot-work crews (see Fig. 2) perform physical tasks together. An important experimental achievement is "teaching" load-hauling robots to use precision guidance algorithms, including visual-based obstacle avoidance, and navigation over uneven terrain. These experiments ensure that robots can manipulate, move and assemble power generators, drilling systems, and laboratories.

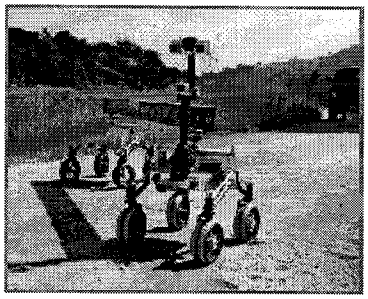

Fig. 2 Two coordinated robots carry large container

In a recent experiment (SCHENKER REFERENCE), two autonomous, coordinated rovers successfully carried a large container about 50m over irregular ground. At one point they autonomously changed formation. Using continuous visual guidance, they successively moved structural beams to the target area.

5. Stepping Stones for Human Exploration

Robotic colonies can establish a permanent presence on asteroids, comets, Jupiter and Saturn's moons—as well as Mars—and open a new era of scientific exploring. By transmitting images and data to Earth from distant surface sites, robotic colonies establish a continued *physical* presence on these worlds, and offer Earth-bound humans a *virtual* presence there. But robot colonists will also place stepping stones on planets and moons, where someday humanity will establish a *physical* presence, continuing—where they left off on our moon thirty years ago—to explore deep space firsthand, alongside their robot companions.

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